Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 1711 – 1721

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

# Thermal dynamic insulation: numerical modeling in a transient regime and application to alternative aviary houses

Fabrizio Ascione[a], Nicola Bianco[a], Claudio De Stasio[a]
Gerardo Maria Mauro[a]*, Giuseppe Peter Vanoli[b],

[a]University of Naples Federico II, DII - Department of Industrial Engineering, Piazzale Tecchio 80, 80125, Naples, Italy
[a]University of Sannio, DING - Department of Engineering, Piazza Roma 21, 82100, Benevento, Italy

**Abstract**

The paper proposes a numerical model for investigating the energy performance of thermal dynamic insulation in transient conditions. This technology consists of porous building components that are permeable to airflow, ensuring high levels of energy performance and IAQ. The model is implemented in MATLAB environment and allows an accurate evaluation of heat transfer through porous media, with the final purpose of quantifying the energy benefits deriving from dynamic insulation. Beyond its presentation, the model is used to investigate the implementation of a dynamically-insulated ceiling to an alternative aviary house for laying-hens, located in Des Moines, Iowa (U.S.). The proposed system produces thermal, energy and economical savings in both cold and warm seasons.


Peer-review under responsibility of Applied Energy Innovation Institute

*Keywords*: Thermal dynamic insulation; Porous media; Transient regime; Numerical model; MATLAB; Aviary houses

## 1. Introduction

Common building envelopes are impermeable to airflow, in order to improve energy performance. Nevertheless, the air change must be guaranteed for regarding Indoor Air Quality (IAQ). How to combine these contrasting requirements? How to conceive a building component that ensures satisfactory levels of energy performance and IAQ? The dynamic insulation technology provides an answer to these questions. It consists of porous components of the building envelope, which are permeable to airflow. In this way, the IAQ is controlled by means of a sufficient airflow [1] and, the thermal insulating qualities of such components improve, compared to the static case (no airflow through the walls), since the thermal resistance is 'dynamic', namely it depends on air velocity [2]. Dynamic insulation systems can work in

* Corresponding author. Tel.: +39-081-7682292; fax: +39-081-2390364.
*E-mail address:* gerardomaria.mauro@unina.it; gerar.mauro@gmail.com


Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.436

two distinct modes [3, 4]: contra-flux and pro-flux. In the first case, air flux and conduction heat flux go in opposite directions, resulting in an increase of the thermal resistance, compared to the impermeable wall. In the second case, the fluxes go in the same direction, resulting in a decrease of the thermal resistance.

Most studies on dynamic insulation, available in current scientific literature, assume simplifying hypotheses, such as steady state conditions. Thus, these are not able to quantify the actual benefits deriving from this technology over the year. In this context, the paper proposes an original numerical model for investigating the energy performance of dynamic insulation in transient conditions, by providing higher accuracy in heat transfer computation. The model is implemented in a home-made code, written in MATLAB environment [5]. This code is run to explore the energy benefits determined by the adoption of a dynamically-insulated ceiling to an alternative aviary house for laying-hens, examined by Zaho *et al.* in static conditions [6], located in Des Moines, Iowa (U.S.). In fact, animal and agricultural storage buildings represent an ideal case to employ dynamic insulation systems [7, 8]. Furthermore, the attention towards alternative aviary houses is more and more increasing all over the world, as confirmed by the European Council Directive 1999/74/EC, which has banned conventional cage housing systems as of 1/1/2012 [9]. In fact, in the conventional houses, the excessive bird stocking density causes cruel living conditions, whereas appropriate values of indoor temperature, relative humidity and air quality are fundamental for hens' welfare, maximum productivity, and efficient feed utilization [10]. However, the reduction of the stocking density, realized in alternative houses, leads to an energy issue, since the internal heat gain decreases; thus, in several cases a supplemental heat generation system is needed [6].

The paper shows how the application of a dynamically-insulated ceiling can reduce or avoid the supplemental heating need in alternative aviary houses, by ensuring energy savings and hens' well-being. Furthermore, the dynamic insulation allows the adoption of a smaller ceiling thickness, since it provides better winter energy performance. This implies a reduction of the investment cost for the ceiling. Finally, compared to a traditional system, also the energy performance during the warm season improves.

**Nomenclature**

| | | |
|---|---|---|
| A | area of the hen house | $m^2$ |
| ACH | air change per hour | $h^{-1}$ |
| BHLF | building heat loss factor | $W\,K^{-1}$ |
| c | specific heat | $J\,kg^{-1}\,K^{-1}$ |
| d | thickness of the dynamically-insulated wall | m |
| I | global horizontal solar irradiance | $W\,m^{-2}$ |
| h | liminar heat transfer coefficient | $W\,m^{-2}\,K^{-1}$ |
| k | thermal conductivity | $W\,m^{-1}\,K^{-1}$ |
| LHP | latent heat production per hen | $W\,kg^{-1}$ |
| MP | moisture production per hen | $kg\,h^{-1}\,hen^{-1}$ |
| m | hen body mass | kg |
| $N_{hens}$ | number of hens | ---- |
| $N_x$ | number of spatial nodes | ---- |
| $n_h$ | ventilation rate per hen | $m^3\,h^{-1}\,hen^{-1}$ |
| $n_{h,max}$ | maximum ventilation rate per hen, for practical issues | $m^3\,h^{-1}\,hen^{-1}$ |
| $n_{h,min}$ | minimum ventilation rate per hen, for humidity control | $m^3\,h^{-1}\,hen^{-1}$ |
| $P_l$ | specific light power | $W\,m^{-2}$ |
| $Q_{gain}$ | sum of heat gains | W |
| $Q_{loss}$ | sum of heat losses | W |
| R | static thermal resistance (R value) of a building component | $m^2\,K\,W^{-1}$ |
| S | area of dynamically-insulated walls | $m^2$ |
| SHP | sensible heat production per hen | $W\,kg^{-1}$ |

| | | |
|---|---|---|
| T | temperature | °C |
| $T_{bal}$ | balance temperature | °C |
| $TD_{25}$ | total temperature discrepancy relative to 25 °C | °C h |
| THP | total heat production per hen | W $kg^{-1}$ |
| TV | total volume of air handled by the fans | $m^3$ |
| t | thickness of the ceiling | m |
| $t_{d,c}$ | thickness of the dynamically-insulated ceiling | m |
| $t_{s,c}$ | thickness of the statically-insulated ceiling | m |
| $U_c$ | static thermal transmittance (U value) of the ceiling | W $m^{-2}$ $K^{-1}$ |
| u | Darcy velocity | m $s^{-1}$ |
| V | volume of the investigated building | $m^3$ |
| x | spatial abscissa | m |
| *Greek symbols* | | |
| α | surface solar radiation absorptance | ---- |
| θ | time | s |
| ρ | density | kg $m^{-3}$ |
| Φ | relative humidity | ---- |
| φ | porosity | ---- |
| ω | humidity ratio | $kg_{water}$ $kg_a^{-1}$ |
| Δθ | time-step size | s |
| *Subscripts* | | |
| a | referred to the air inside the porous medium | ---- |
| e | equivalent property of the porous medium | ---- |
| i | referred to inside | ---- |
| o | referred to outside | ---- |
| s | referred to the solid matrix of the porous medium | ---- |

## 2. Numerical Model

In the investigation of heat transfer through porous media, the following hypotheses are assumed:

- the material is homogeneous and isotropic, with constant thermo-physical properties;
- heat and air fluxes are one-dimensional; they are parallel to the spatial abscissa x, which is perpendicular to the largest surface of the wall and directed from outdoor to indoor environment;
- the Darcy velocity (u) is constant and is assumed to be positive in the direction of increasing x;
- the local thermal equilibrium (LTE) occurs and the Darcy regime subsists ($u \approx 10^{-3} \div 10^{-4}$ $ms^{-1}$).

In these assumptions, the energy balance for a porous medium [11] is expressed by equation (1), which can be simplified in equation (2) for dynamic insulation systems (ρs >> ρa) [12].

$$\left((1-\varphi)\cdot k_s+\varphi\cdot k_a\right)\frac{\partial^2 T}{\partial x^2}=\left((1-\varphi)\cdot\rho_s\cdot c_s+\varphi\cdot\rho_a\cdot c_a\right)\frac{\partial T}{\partial\theta}+u\cdot\rho_a\cdot c_a\frac{\partial T}{\partial x} \quad (1)$$

$$k_e\frac{\partial^2 T}{\partial x^2}=\rho_e\cdot c_s\frac{\partial T}{\partial\theta}+u\cdot\rho_a\cdot c_a\frac{\partial T}{\partial x} \quad (2)$$

Equation (2) requires the definition of an initial condition and two boundary conditions. Here, an uniform initial temperature is set, while the boundary conditions are expressed by equations (3) and (4).

$$-k_e \frac{\partial T(0,\theta)}{\partial x} = h_o \left(T_o(\theta) - T(0,\theta)\right) + \alpha \cdot I$$
(3)

$$k_e \frac{\partial T(d,\theta)}{\partial x} = h_i \left(T_i(\theta) - T(d,\theta)\right) \quad (4)$$

Equation (2) is solved by means of a finite difference method, implemented in the developed MATLAB code. The Crank-Nicolson approach is adopted. More in detail, both spatial and temporal domains are discretized, by generating $N_x$ spatial nodes and time-steps of size equal to $\Delta\theta$. Finally, a zero-dimensional approach is used for modeling the energy behavior of a building, separated from outside through a (totally or partially) dynamically-insulated envelope. The energy balance for a control volume enclosing the building is reported in equations (5) and (6), respectively for the contra-flux and the pro-flux mode.

$$\rho_a \cdot c_a \cdot V \frac{\partial T_i(\theta)}{\partial \theta} = Q_{gain}(\theta) - Q_{loss}(\theta) + |u| \cdot S \cdot \rho_a \cdot c_a \cdot \left(T(d,\theta) - T_i(\theta)\right) - k_e \cdot S \frac{\partial T(d,\theta)}{\partial x} \quad (5)$$

$$\rho_a \cdot c_a \cdot V \frac{\partial T_i(\theta)}{\partial \theta} = Q_{gain}(\theta) - Q_{loss}(\theta) + |u| \cdot S \cdot \rho_a \cdot c_a \cdot \left(T_o(\theta) - T(d,\theta)\right) - k_e \cdot S \frac{\partial T(d,\theta)}{\partial x} \quad (6)$$

$Q_{gain}$ is the sum of internal heat gains, deriving from the presence of any heat sources. $Q_{loss}$ is the sum of heat losses from inside to outside, except for those through the 'dynamic walls'; thus, it represents the thermal power dispersed through the statically-insulated part of the building envelope.
After spatial and temporal discretizations, equation (5) (in contra-flux), or equation (6) (in pro-flux), is solved together with equation (2), by means of the finite difference method. In particular, an algebraic system of $N_x$+1 equations is solved at each time-step, for assessing the temporal trend of $T_i$.

## 3. Case study

### *3.1. Alternative aviary house*

The geometrical peculiarities and thermo-physical properties of the aviary house are shown in Table 1. As said, this reference system is taken from [6] and is located in Des Moines, Iowa (U.S). The shape is rectangular, with a high amount of ceiling area in terms of percentage of dispersing surface. The ceiling is made of cellulose, characterized by [13]: $k_e$ = 0.04 W $m^{-1}$ $K^{-1}$, $c_e$ = 1100 J $kg^{-1}$ $K^{-1}$, $\rho_e$ = 95 kg $m^{-3}$, $\varphi$ = 90%.

Table 1.Geometrical and thermal characterization of the investigated aviary house, investigated by Zhao et al. [6]

| Alternative aviary house with white hens [6] | | | |
|---|---|---|---|
| Building | | Hens | |
| Dimensions (L × W × H) [m] | 141 × 52 × 3 | Number of hens ($N_{hens}$) | 107000 |
| Door area [$m^2$] | 20 | Hen mass (m) [kg] | 1.5 |
| Fan area [$m^2$] | 59 | THP during light period at 24 °C [W $kg^{-1}$] | 7.2 |
| R-value [$m^2$ $KW^{-1}$] | | THP during dark period at 24 °C [W $kg^{-1}$] | 5.4 |
| • Perimeter walls | 2.65 | | |
| • Ceiling (0.2 m tick cellulose) | 5.30 | Indoor set points | |
| • Doors | 0.29 | Temperature [°C] | 25 |

| | | | |
|---|---|---|---|
| • Fans | 0.15 | Relative Humidity [%] | 60 |
| Perimeter heat loss factor [W m$^{-1}$ K$^{-1}$] | 1.6 | Specific light power [W m$^{-2}$] | 2.2 |
| Building heat loss factor (BHLF) [W K$^{-1}$] | 2840 | | |
| Solar radiation absorptance of the roof (α) | 0.3 | | |

The building envelope is air impermeable. The ventilation rate ($n_h$) for humidity and temperature control is ensured by a mechanical system. A maximum value of ACH equal to 60 h$^{-1}$ is imposed for practical issues, resulting in a maximum value ($n_{h,max}$) of $n_h$. The system operates according to the following logic:

- if $T_i$< 28 °C, $n_h$ is set equal to the minimum value needed for humidity control ($n_{h,min}$);
- if $T_i$ > 28°C and $T_o$ < 26°C, $n_h$ assumes the minimum value that ensures an indoor temperature lower than 28 °C at the next time step, if ACH results lower than 60 h$^{-1}$; otherwise $n_h$ is set equal to $n_{h,max}$;
- if $T_i$ > 28°C and $T_o$ ≥ 26°C, $n_h$ assumes the minimum value, that ensures an indoor temperature lower than ($T_o$ + 2) °C at the next time step, if ACH results lower than 60 h$^{-1}$; otherwise $n_h$ is set equal to $n_{h,max}$.

The temperature of 28 °C is chosen as threshold-value, because higher values are harmful for hens [14].

### *3.2. Proposed system: dynamically-insulated ceiling*

The implementation of a dynamically-insulated ceiling to the aviary house is investigated. The 'dynamic ceiling' is made of the same material of the 'static ceiling' (present in the reference system), namely cellulose, but it is air permeable, by virtue of the adoption of an appropriate plaster. A smart alternation between contra-flux and pro-flux mode is realized, by means of a dedicated mechanical ventilation system:

- if $T_i$ < 25 °C (set point temperature), the contra-flux mode is on, in such a way that the thermal resistance of the ceiling increases compared to the static case (R-value);
- if $T_i$ ≥ 25 °C, the pro-flux mode is on, in such a way that the thermal resistance of the ceiling decreases.

The purpose is to achieve values of the indoor temperature that are closer to the set point temperature compared to the reference system, with consequent thermal and energy benefits. The entity of the ventilation rate varies in function of $T_i$ and $T_o$, with the same logic described in subsection 3.1.

In order to solve the equations (2), (5) and (6), some terms are explicated in relation to the case study:

$$Q_{gain}(\theta) = A \cdot P_l + m \cdot N_{hens} \cdot SHP \tag{7}$$

$$Q_{loss}(\theta) = \left(BHLF - A \cdot U_c\right) \cdot \left(T_i(\theta) - T_o(\theta)\right) \tag{8}$$

$$|u| = \frac{n_h \cdot N_{hens}}{S \cdot 3600} \tag{9}$$

The THP and the SHP are calculated in function of T by means of the expressions proposed, respectively, in [15] and [6]. The LHP is the difference between THP and SHP. Finally, $n_{h,min}$ is given by equation (10), where the MP is computed from the LHP.

$$n_{h,\min} = \frac{MP}{\rho_a \cdot (\omega_i - \omega_o)} \tag{10}$$

## 4. Results and discussion

The benefits of the proposed system on the energy and thermal behavior of the aviary house are explored in two stages: I) during the winter season (subsection 4.1); II) over the entire year (subsection 4.2).

A time-step of 900 s and a mesh with 100 nodes are adopted in order to ensure a good compromise between the computational effort and the reliability of results. The initial temperature of the ceiling is set equal to 25 °C. Furthermore, the indoor and outdoor liminar heat transfer coefficients are set respectively equal to 10 $W\,m^{-2}\,K^{-1}$ and 25 $W\,m^{-2}\,K^{-1}$. The trends of $T_o$ and $\Phi_o$ are taken from climatic TMY3 dataset.

The static and dynamic (proposed system) configurations of the ceiling are compared in terms of:

- temporal trends of the indoor temperature ($T_i$);
- temporal trend of the absolute difference between $T_i$ and 25 °C (set point temperature);
- temporal trend of the ventilation rate per hen ($n_h$);
- temporal trend of the ratio between $n_h$ and the minimum ventilation rate for humidity control ($n_{h,min}$);
- balance temperature ($T_{bal}$);
- total temperature discrepancy relative to 25 °C ($TD_{25}$);
- total volume of airflow handled by the fans (TV).

In the above reported bullet list, $T_{bal}$ is the outdoor temperature below which a heat generation system is required to maintain the set point temperature. Furthermore, $TD_{25}$ is calculated by equation (11), where $N_t$ is the number of time steps. It represents a measure of how much and how long $T_i$ moves away from 25 °C: the lower this parameter, the higher the energy performance of the building.

$$TD_{25} = \frac{\sum_{j=1}^{Nt} 900 \cdot \left| T_i(\theta_j) - 25 \right|}{3600} \tag{11}$$

The analysis is carried out for two different hen stocking densities: $N_{hens}$ is initially set equal to 107000 as in [6] and, then, is changed to 66000, in order to ensure a density respectful of the hens' welfare, namely 9 hens $m^{-2}$ [9]. Furthermore, in order to point out the benefits provided by dynamic insulation, the simulations have been performed for three different thicknesses of the dynamic (i.e., $t_{d,c}$) and static (i.e, $t_{s,c}$) configurations of the ceiling, namely 0.2 (as in [6]), 0.1 and 0.05 m. It is noticed that when $t_{d,c}$ and $t_{s,c}$ are equal, both of them are denoted with t. The results will show that the proposed system allows the adoption of smaller thicknesses, since it ensures better energy performance in the cold period. This could imply a further saving due to lower investment cost for the realization of the ceiling, and, also, an improvement of summer energy performance, because the rate, at which the high internal gain is dissipated, increases.

### *4.1. Investigation during the winter season*

Figure 1 shows the results obtained in correspondence of $N_{hens}$ = 107000 and t = 0.02 m, in terms of $T_i$, $|T_i$ - 25°C|, $n_h$ and $n_h/n_{h,min}$. Similar trends occur for the other two ceiling's thicknesses (i.e., 0.1 and 0.05 m), but when t decreases, also $T_i$ and the ventilation demand for temperature control tend to decrease, since the thermal resistance of the building envelope is reduced. The dynamic insulation, compared to the static case, determines values of $T_i$ that are generally closer to 25 °C. This is due to the smart alternation between the contra-flux and the pro-flux mode. Therefore, the proposed system improves the thermal welfare of hens and implies an energy saving as well. Indeed, the need of a supplemental heat generation system, necessary for maintaining acceptable conditions in correspondence of low outdoor temperatures, is avoided or reduced. On the other hand, it generally induces a slightly higher ventilation demand for temperature control. Indeed, the implementation of dynamic insulation leads to lower values of $T_{bal}$: thus, in most hours of the winter season (when $T_o > T_{bal}$) the temperature is merely controlled by adequately setting a value of $n_h$ higher than $n_{h,min}$. On the contrary, in the static configuration, the values of $T_{bal}$ are greater: thus, in several hours (when $T_o < T_{bal}$) of the winter season, $n_h$ is set equal to $n_{h,min}$ and the temperature control should be realized by the supplemental heating system (which is not considered in the simulations).

The previous observations are confirmed by Table 2, where $T_{bal}$, $TD_{25}$ and TV are reported for the three thicknesses. As expected, the 'dynamic ceiling' induces a reduction of $T_{bal}$ and $TD_{25}$, in spite of an increment of TV. However, the thermal benefit is more significant compared to the increase of ventilation demand. More in detail, for t equal to 0.2, 0.1, 0.05 m, the percentage reduction of $TD_{25}$ is respectively equal to 9.3%, 17.5%, 37.4%, while the percentage increment of TV is equal to 5.6%, 4.6%, -4.2%. The latter negative value occurs because the 0.05 m thick ceiling produces, in the static case, very low values of $T_i$, and, consequently, of $\omega_i$: thus, $n_{h,min}$ increases (eq. 10). As a result, when t is equal to 0.05 m, the dynamic insulation generates a double benefit, in terms of energy savings for both heating and ventilation.

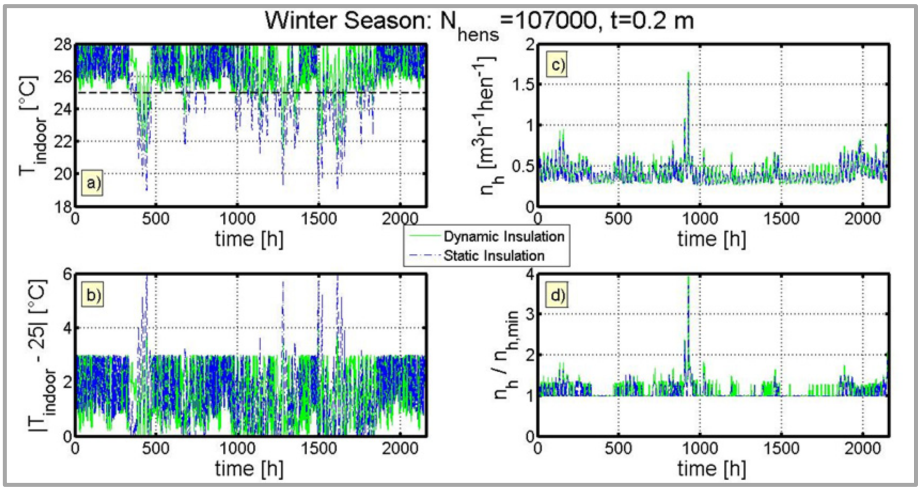



Fig. 1. Aviary house with 107000 hens and a 0.2 m tick ceiling. Temporal trends during the winter season of: a) indoor temperature; b) absolute difference between indoor temperature and 25 °C; c) ventilation rate; d) ratio between ventilation rate and minimum ventilation rate for humidity control

Table 2. Comparison between dynamic and static insulation of the ceiling, as for winter performance in function of the ceiling thickness, in a house with 107000 hens.

| Winter Season $N_{hens}$ = 107000 | $T_{bal}$ [°C] | | $TD_{25}$ [°C h] | | TV [$m^3$] | |
|---|---|---|---|---|---|---|
| | Dynamic Insulation | Static Insulation | Dynamic Insulation | Static Insulation | Dynamic Insulation | Static Insulation |
| t = 0.2 m | -15 | -9.4 | $3.61 \cdot 10^3$ | $3.98 \cdot 10^3$ | $9.80 \cdot 10^7$ | $9.28 \cdot 10^7$ |
| t = 0.1 m | -15 | -6.1 | $3.63 \cdot 10^3$ | $4.40 \cdot 10^3$ | $9.78 \cdot 10^7$ | $9.35 \cdot 10^7$ |
| t = 0.05 m | -9.4 | 0.5 | $3.85 \cdot 10^3$ | $6.15 \cdot 10^3$ | $9.58 \cdot 10^7$ | $1.00 \cdot 10^8$ |

Overall, when t decreases, the favorability of the proposed system is amplified, since the thermal resistance of the 'static ceiling' gets very meager, while the 'dynamic ceiling' retains good insulating qualities thanks to the contra-flux mode. This trend is confirmed by the values assumed by $T_{bal}$, when t varies from 0.2 to 0.05 m. Indeed the increment of $T_{bal}$ is much more significant in the static case: it varies from -9.4°C to 0.5°C, while in the dynamic case it varies from -15 °C to -9.4 °C. It is noted that the balance temperature achieved in presence of the 'static ceiling' with a thickness of 0.2 m (reference system) corresponds to that evaluated by Zhao et al. [6] for the same case study, namely -9.4 °C. Eventually, if the lowest acceptable $T_i$ for the wellness of hens and their maximum productivity is set equal to 18 °C [16], the minimum thickness of the ceiling is equal to 0.05 m in the dynamic case and 0.1 m in the static case.

In a second stage, the same analysis has been carried out in correspondence of $N_{hens}$ = 66000. The new values of $T_{bal}$, $TD_{25}$ and TV are reported in Table 3. In comparison with the case of 107000 hens:

- the values of $T_{bal}$ are higher, because of the reduced internal gain (see eq. 7);
- the values of $TD_{25}$ are higher, too (for the previous reason);
- the values of TV are lower, because of the reduced ventilation demand in presence of a less hens.

Table 3. Comparison between dynamic and static insulation of the ceiling, as for winter performance in function of the ceiling thickness, in a house with 66000 hens

| Winter Season $N_{hens}$ = 66000 | $T_{bal}$ [°C] | | $TD_{25}$ [°C h] | | TV [$m^3$] | |
|---|---|---|---|---|---|---|
| | Dynamic Insulation | Static Insulation | Dynamic Insulation | Static Insulation | Dynamic Insulation | Static Insulation |
| t = 0.2 m | -11.7 | -6.1 | $3.88 \cdot 10^3$ | $4.33 \cdot 10^3$ | $5.85 \cdot 10^7$ | $5.75 \cdot 10^7$ |
| t = 0.1 m | -8.9 | 1.4 | $4.00 \cdot 10^3$ | $5.90 \cdot 10^3$ | $5.82 \cdot 10^7$ | $6.13 \cdot 10^7$ |
| t = 0.05 m | -2.8 | 4.1 | $4.80 \cdot 10^3$ | $1.09 \cdot 10^4$ | $5.92 \cdot 10^7$ | $6.75 \cdot 10^7$ |

Notably, for t equal to 0.2, 0.1, 0.05 m, the dynamic insulation induces a percentage reduction of $TD_{25}$ respectively equal to 10.4%, 32.2%, 56.0%, as well as a percentage increment of TV equal to 1.7%, -5.1%, -12.3%. The proposed system gets more effective when the stocking density decreases, because the internal heat gain decreases and, consequently, lower values of $T_i$ occur; this induces a diminution of $\omega_i$, and, thus, an increment of $n_{h,min}$ when $T_i$ is particularly low. This effect is more marked in the static case because of the smaller values assumed by thermal resistance. Therefore, for decreasing stocking densities, the dynamic insulation tends to produce a double increasing benefit. First, the thermal benefit, related to $TD_{25}$ reduction, is amplified. Secondly, the expected increment of the ventilation demand becomes a decrement, because of the high values assumed by $n_{h,min}$ in the static case. Eventually, if the lowest acceptable $T_i$ is 18 °C [16], the minimum ceiling's thickness is equal to 0.1 m in the dynamic case ($t_{c,d}$) and 0.2 m in the static case ($t_{s,d}$).

### *4.2. Investigation over the year*

The annual investigation is performed for both considered hen stocking densities, namely $N_{hens}$ equal to 107000 and 66000, in correspondence of the minimum values of the ceiling thickness, which ensure acceptable winter thermal performance. In particular the two analyzed case studies are:

- case study 1: $N_{hens}$ = 107000, $t_{d,c}$ = 0.05 m, $t_{s,c}$ = 0.1 m;
- case study 2: $N_{hens}$ = 66000, $t_{d,c}$ = 0.1 m, $t_{s,c}$ = 0.2 m.

The outcomes obtained for case 1 are reported in Figure 2 in terms of $T_i$, $|T_i$ - 25°C|, $n_h$ and $n_h/n_{h,min}$. The same trends, achieved for case 2, are omitted, because they provide identical observations.

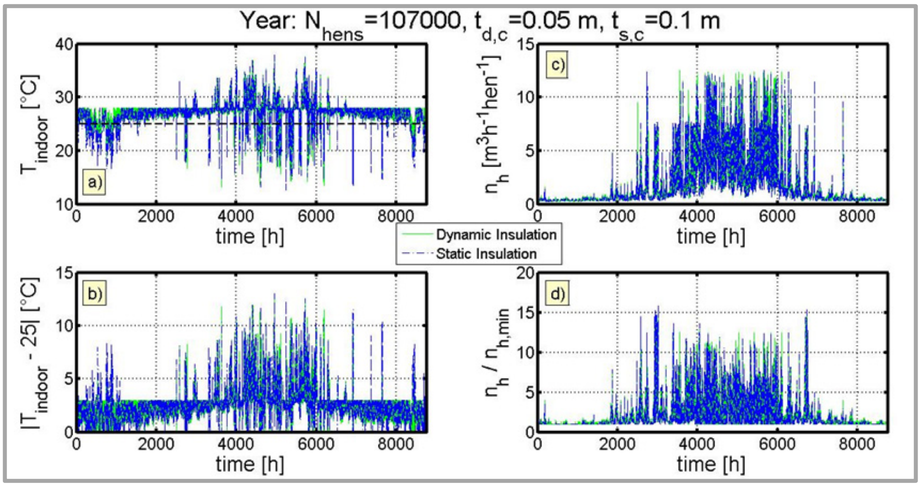



Fig. 2. Case study 1: temporal trends over the year of: a) indoor temperature; b) absolute difference between indoor temperature and 25°C; c) ventilation rate; d) ratio between ventilation rate and minimum ventilation rate for humidity control

The main difference, compared to the winter investigation, is due to the huge ventilation rates for temperature control, needed during the warm season. It is recalled that the ACH should be lower than the maximum ACH, set equal to 60 $h^{-1}$. That's why, in several hours, the values of $T_i$ are very high, both in presence of static and dynamic insulation. In these cases, higher ventilation rates are required by means of large openings in the building envelope, and thus the dynamic insulation behaves alike the static one. Otherwise, during the warm season, the proposed system works in pro-flux mode. In this way the thermal resistance of the ceiling is lower compared to the static case and, consequently, the rate, at which the high internal gain is dissipated through the building envelope, increases. This leads to a reduction of ventilation demand for temperature control. However, this benefit is quite slight because of the magnitude of the ventilation load, which determines a marginal role for the heat transfer through the envelope. Table 4 reports the values assumed by $TD_{25}$, TV and $T_{bal}$ for the two case studies. The proposed system produces a double annual benefit, in terms of reduction of $TD_{25}$ and TV, in both cases:

- case study 1: decrement of 1.7% for $TD_{25}$ and of 0.61% for TV;
- case study 2: decrement of 1.7% for $TD_{25}$ and of 0.97% for TV.

Table 4. Comparison over the year between dynamic and static insulation of the ceiling, in presence of ceiling thicknesses which ensure satisfactory winter performance ($T_{indoor}$>18°C) respectively in the cases of 107000 and 66000 hens

| Annual performance | | $T_{bal}$ [°C] | | $TD_{25}$ [°C h] | | TV [$m^3$] | |
|---|---|---|---|---|---|---|---|
| | | Dynamic Insulation | Static Insulation | Dynamic Insulation | Static Insulation | Dynamic Insulation | Static Insulation |
| CASE 1 | $N_{hens}$ = 107000<br>$t_{d,c}$ = 0.05 m<br>$t_{s,c}$ = 0.1 m | -9.4 | -6.1 | $2.31 \cdot 10^4$ | $2.35 \cdot 10^4$ | $1.64 \cdot 10^9$ | $1.63 \cdot 10^9$ |
| CASE 2 | $N_{hens}$ = 66000<br>$t_{d,c}$ = 0.1 m<br>$t_{s,c}$ = 0.2 m | -8.9 | -6.1 | $2.29 \cdot 10^4$ | $2.33 \cdot 10^4$ | $1.04 \cdot 10^9$ | $1.03 \cdot 10^9$ |

It is evident that the reported percentage reductions are quite smaller compared to the benefits achieved in winter time. In fact, the benefit induced by dynamic insulation in the warm season is very slight, as previously argued. Moreover, the high values assumed by $T_i$ and $n_h$ in the warm season cause a significant increase of $TD_{25}$ and TV calculated over the year for both dynamic and static insulation. Finally, there is a reduction of the percentage weight of the benefit induced by the proposed system.

## Conclusions

A numerical model has been developed for analyzing the energy performance of dynamically-insulated systems in transient conditions. The model has been implemented in a MATLAB code and run for exploring the benefits induced by a dynamically-insulated ceiling, applied to an alternative aviary house for laying-hens. The proposed system is based on a smart alternation between the contra-flux mode the pro-flux mode. The analysis has been performed in two stages: I) during the winter season; II) over the year. In both cases, two hen stocking densities have been considered, corresponding to a number of hens respectively equal to 107000 and 66000. Concerning the winter season, the 'dynamic ceiling' produces the following benefits, compared to a 'static ceiling' of the same thickness and material: *a)* the indoor temperatures are closer to the set point temperature in most hours of the season; *b)* a reduction of the balance temperature occurs, and, thus, the need of a heating system is avoided or reduced: this results in an energy saving; *c)* when the thickness of the ceiling is particularly small (i.e.. 0.05 m), the ventilation demand is reduced. When the bird stocking density decreases, the described benefits increase. Eventually, the dynamic insulation allows the adoption of smaller thicknesses, because of its higher insulating qualities. This could also imply a reduction of the investment cost for the realization of the ceiling.

The annual investigation is carried out for two case studies, one for each stocking density, characterized by the minimum values of the ceiling thickness, which ensure appropriate winter thermal performance. In both cases, the 'dynamic ceiling' determines an improvement of indoor thermal conditions and a decrease of ventilation demand. However, the percentage benefits are reduced compared to the winter season. Indeed, the favorability of dynamic insulation in the warm season is very slight, because of the huge ventilation rate necessary for temperature control.

## References

[1] Imbabi MS. Modular breathing panels for energy efficient, healthy building construction. *Renew Energ* 2006;**31**:729−38.

[2] Taylor BJ, Imbabi MS. The application of dynamic insulation in buildings. *Renew Energ* 1998;**15**:377−82.

[3] Taylor BJ, Cawthorne DA, Imbabi MS. Analytical investigation of the steady-state behaviour of dynamic and diffusive building envelopes. *Build Environ* 1996;**31**:519−25.

[4] Taylor BJ, Imbabi MS. The effect of air film thermal resistance on the behaviour of dynamic insulation. *Build Environ* 1997;**32**:397−404.

[5] MATLAB - MATrix LABoratory - 7.10.0. *User's Guide*, MathWorks; 2010.

[6] Zhao Y, Xin H, Shepherd TA, Hayes MD, Stinn, JP. Modelling ventilation rate, balance temperature and supplemental heat need in alternative vs. conventional laying-hen housing systems. *Biosystems Engineering* 2013;**115**:311–23.

[7] Clare AD, Etheridge DW. Dynamic Insulation–Recent Experimental and Theoretical Studies. In *Proc. 22nd AIVC Conference*; September, 2001.

[8] Kuczyński, T, Przybyła, K. Porous ceiling air inlet as a potential source of uncontrolled air exchange at nurseries with exhaust mechanical ventilation. Agricultural Engineering 2002;5:02.

[9] CEC. Council Directive 1999/74/EC laying down minimum standards for the protection of laying hens. Brussels, Belgium: Commission of the European Communities (CEC); 1999.

[10] Dawkins MS, Donnelly CA, Jones, TA. Chicken welfare is influenced more by housing conditions than by stocking density. Nature 2004;427(6972):342–344.

[11] Nield DA, Bejan A. Convection in Porous Media. 4th ed. Springer; 2013.

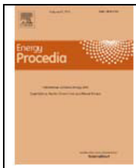
[12] Ascione F, Bianco N, De Stasio C, Mauro GM, Vanoli GP. Dynamic insulation of the building envelope: numerical modeling under transient conditions and coupling with nocturnal free cooling. *Applied Thermal Engineering* 2015;**84**:1−14.

[13] Bjork F, Odeen K. Transport of air, tracer gas, and moisture through a cellulose fibre insulated structure. *Nordic Journal of Building Physics* 1997;**21**:217−28.

[14] Li Y, Ito T, Nishibori M., Yamamoto S. Effects of environmental temperature on heat production associated with food intake and on abdominal temperature in laying hens. *British poultry science* 1992;**33**:113–22.

[15] Pedersen S, Sallvik K. *Fourth report of working group on climatization of animal houses: Heat and moisture production at animal and house levels*. Horsens, Denmark: Research Centre Bygholm, Danish Institute of Agricultural Sciences; 2004.

[16] Thiele HH, Pottgüter R. Management recommendations for laying hens in deep litter, perchery and free range systems. *Lohmann Information* 2008;**43**:53-63.




**Biography**

Gerardo Maria Mauro – Ph.D. student in Engineering of Mechanical Systems – is Researcher in Applied Thermodynamics and Heat Transfer for Buildings at the University of Naples Federico II, Department of Industrial Engineering (DII). He focuses his research activity on the analysis of innovative components of the building thermal envelope, as well as on the simulation-based optimization of building energy performance